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A CORRELATIONAL STUDY OF MYOPOTENTIAL RESPONSE AND FORCE OF MUSCLE
CONTRACTION DURING VARYING ACTIVITY DEMANDS

Interim Report

Prepared for
The Office of Naval Research
Psychological Sciences Division
Engineering Psychology Branch
Washington, D. C.

Contract No. Nonr 4292(00)
Philco No. 2386

March 17, 1965

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I. INTRODUCTION

A major objective of the Philco Bio-Cybernetics Engineering activity has been to develop an optimum degree of compatibility between man and the machines which he used to augment his performance capacity. One phase of study, in the pursuit of this objective, has been developed about a hypothesis that the myoelectric activity associated with muscular contraction could be utilized to control a powered exo-skeletal system designed to amplify one's strength. This phase of study is covered under the current ONR contract which is the subject of this interim report.

Systems such as mentioned above are typically seen in the rehabilitation of the disabled in the form of prosthetic and orthotic devices used in the practice of orthopedic medicine. The application of external power to these type devices holds great promise not only for bringing the sub-strength individual to a useful performance level, but also in providing performance capability for the normal which is beyond ordinary performance limits (i.e., performance under extreme g-forces, in so-called hostile environments, etc.).

The feasibility of utilizing myoelectric signals to actuate a control system was clearly demonstrated in the first phase of the ONR study (Contract No. Nonr 4292(00)). Utilizing test equipment (Myocoder, Figure 1) and a computer analysis (Multinorm), both developed on Philco assigned discretionary funds, the following was accomplished:

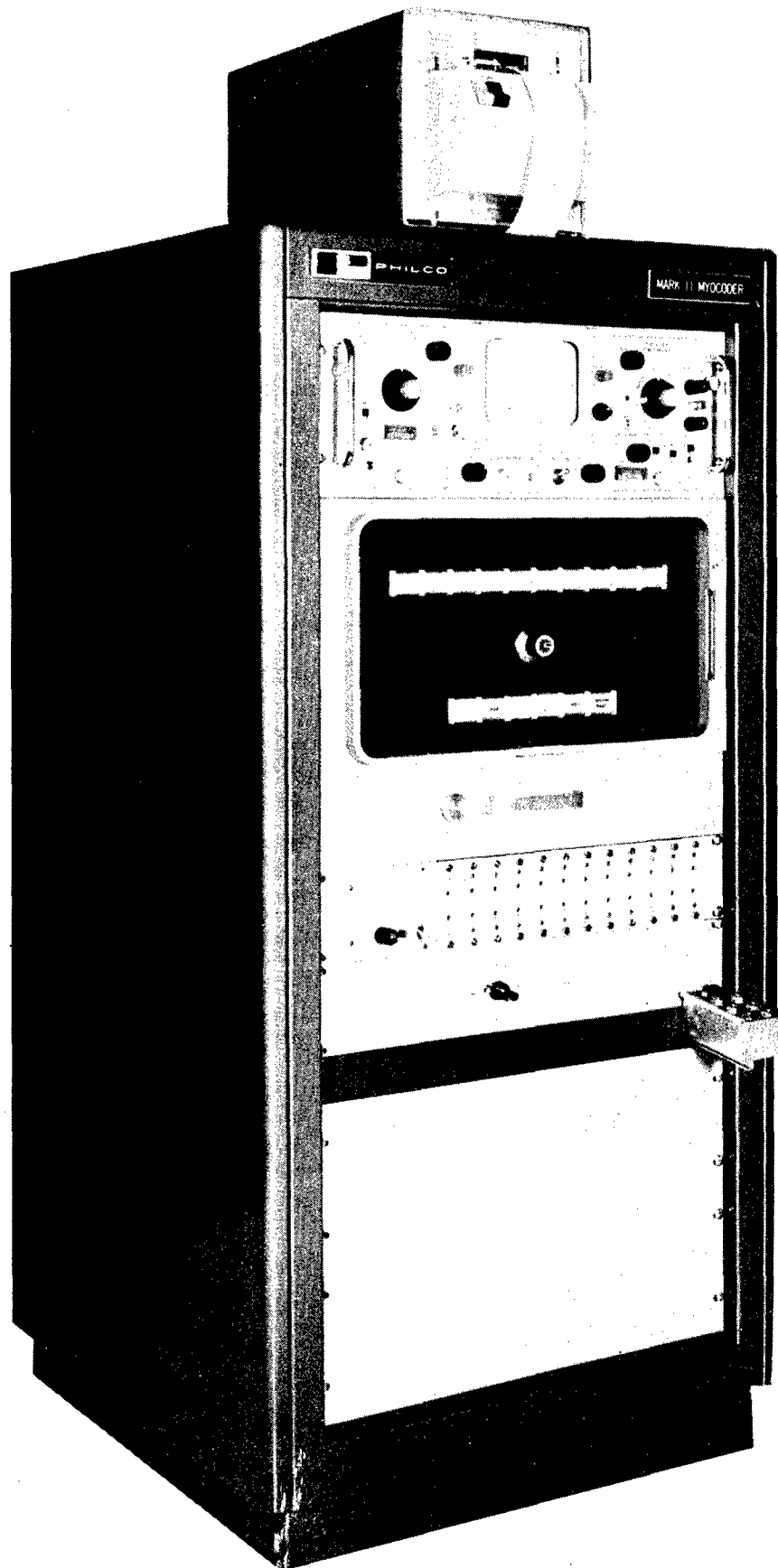


Figure 1 - Philco Myocoder

The electronic system complex used to detect, amplify, process and code myoelectric data rendering it in compatible format for statistical analysis by the Philco S-2000 Computer.

1. Myoelectric activity can be coded and rendered compatible for computer analysis. (The rationale for the coding process was based upon the direct relationship between the energy value of the myoelectric signal and the force exerted by the contracting muscle. See Figure 2.)
2. Computer techniques can be used to analyse coded myoelectric data and print the results in a form which allows discrimination between two classes of preprocessed myoelectric patterns, obtained from identical signal sources (i.e., same muscles) while performing different motions.

The clear advantages of the development of a control system technology based on the myoelectric-computer approach are as follows:

1. A natural motion sequence can be utilized and there would be no dependence on specially learned command motions.
2. The latency between operator initiation of motion and system actuation would be minimal.
3. The computer generated discriminant weighting function specifies the discriminant networks necessary to identify discrete motions in a functional system.

The next step following the first study was apparent. Determination of the total system reliability was required. Such determination therefore, has been the focus of the second study, ("A Correlational Study of Myopotential Response and Force of Muscle Contraction During Varying Activity Demands").

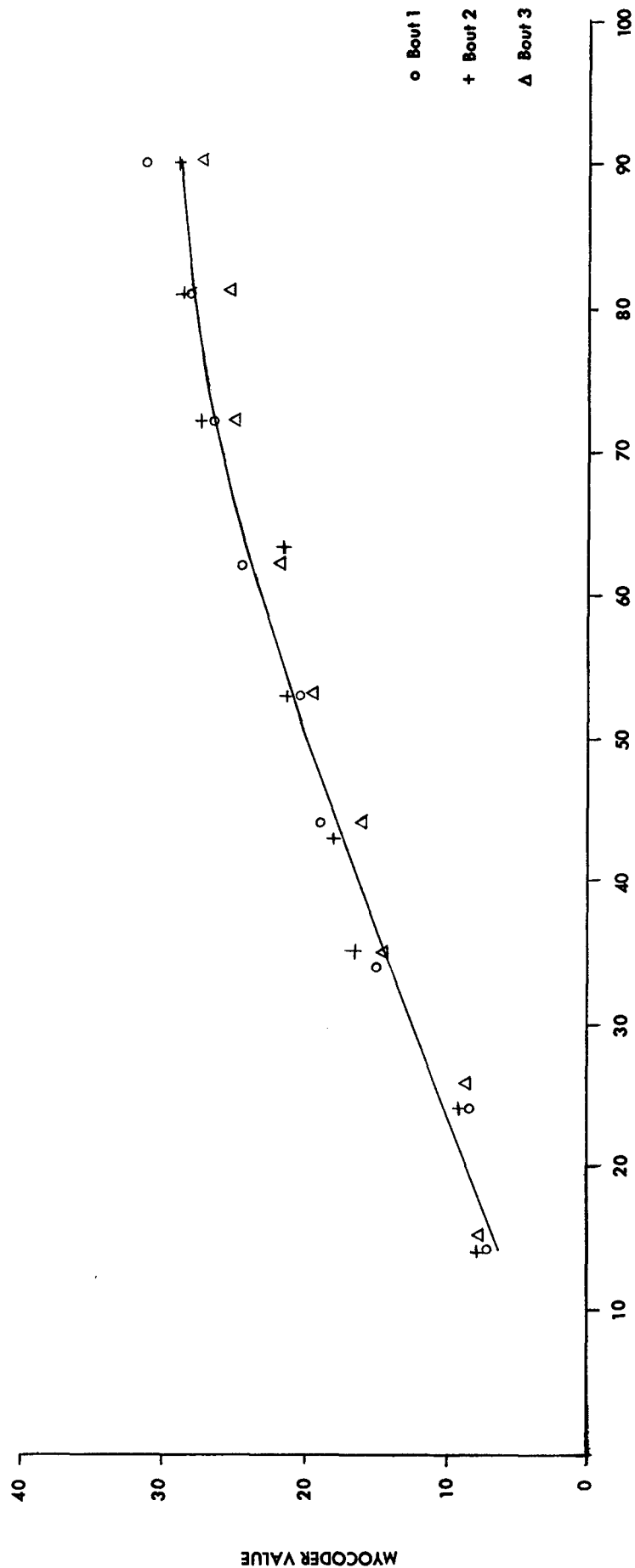


Figure 2. Curve of Best Fit Average Myoelectric Energy Values for the Anterior Deltoid During Shoulder Flexion. Five samples each were obtained for three bouts of activity. The contraction was isotonic.

Determining reliability of the total system involves systematic studies of physiological and equipment performances. Critical issues in either performance variable have common implications for problem identification and clarification. Therefore, the physiological and equipment phases of study have been pursued simultaneously. However, this report deals only with the physiological performance. A later report will treat equipment performance.

II. PURPOSE OF THE STUDY

The feasibility of utilizing electrical potentials on the surface of the skin for control functions was successfully demonstrated in the first ONR study*. However, in the wake of this study, a critical issue remained which involved the reliability of the myoelectric pattern used for discriminating a control command for a discrete motion. Since the changing energy value of each signal source was the basis for identification of the control command, it became evident that it was important to study those factors or conditions which could alter the myoelectric pattern. Obviously the assumption could be made that since each signal content was a function of the force of muscle contraction, any change in mass or acceleration could alter the signal content. No alteration in mass or acceleration was considered in the first study. The command motion involved displacement of the limb at as constant a velocity as the subject could execute and with no load imposed other than the effect of gravity acting on the body member.

Variability in the signal content during the execution of a motion could conceivably reduce, or even cancel, the value of the discriminant network for a functional system. Effects of position and force, for example, could

* A Study to Investigate the Feasibility of Utilizing Electrical Potentials on the Surface of the Skin for Control Functions. A Report to the Office of Naval Research, Contract No. Nonr 4292(00), Philco Corporation, July 1, 1964.

introduce such variations into the signal content. The importance of studying this variability lies in the desire to initiate proper control commands within a broad range of limb positions and to drive the motions at velocities commensurate with requirements for human, not robot-like performance.

Therefore, the network for the functional system must include weighting functions which discriminate, at the initiation of activity, not only the plane of reference and sequence of motion, but the temporal pattern intended as well. The purpose of this investigation then, is to systematically study varying activity demands together with their coincident myopotential response, and to correlate these responses to the force of muscle contraction.

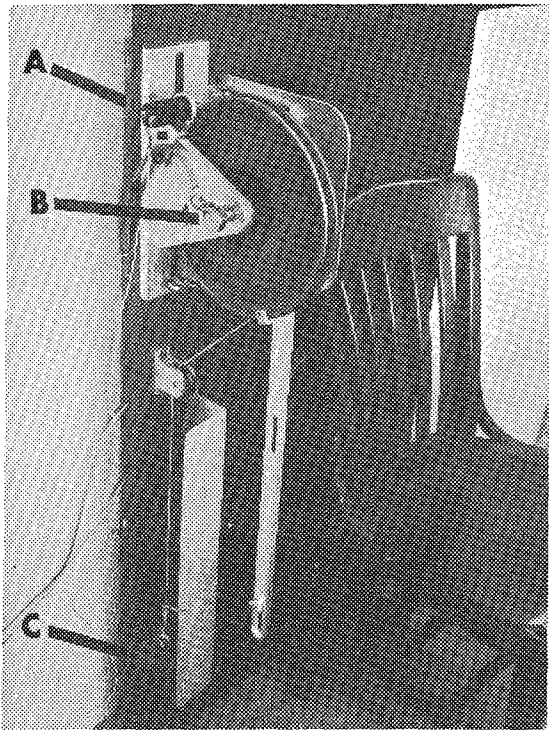
III. METHODS AND MATERIALS

A. Equipment

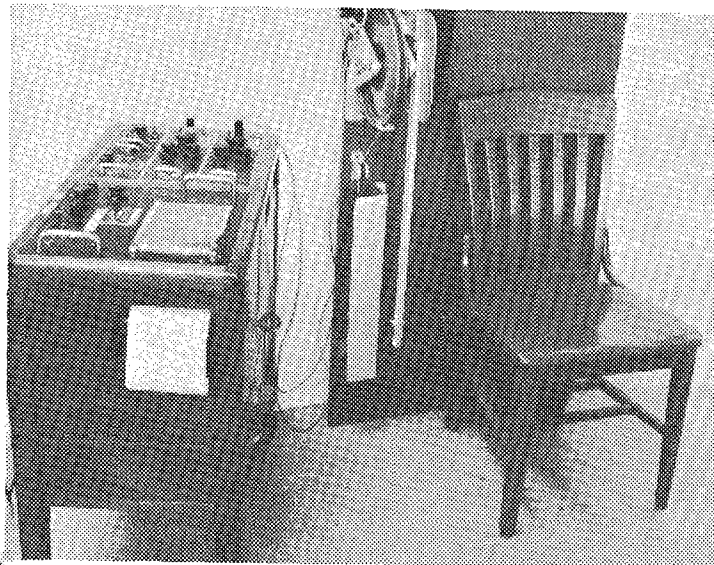
The equipment used to make measurements include the Myocoder and the ergograph. The Myocoder has been described previously. The ergograph was designed and constructed to measure motion and force parameters of shoulder and elbow flexion in the sagittal plane. The ergograph is shown in Figures 3-1, -2, -3 and -4. Figure 3-1 shows a close-up view of the load subassembly of the ergometer and identifies components such as the tachometer (A), potentiometer (B), and the weight (C). Figure 3-2 shows the ergograph assembly consisting of the ergometer and the recorder. Figures 3-3 and 3-4 show a subject seated in the ergometer utilizing the shoulder and elbow flexion positions, respectively.

1. Ergometer

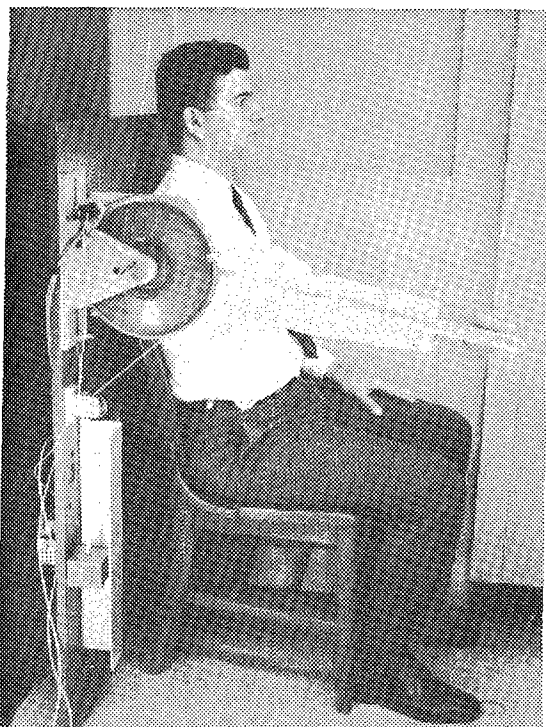
The ergometer consists of a chair attached to a backboard, a load subassembly supported by the backboard and the instrumentation.



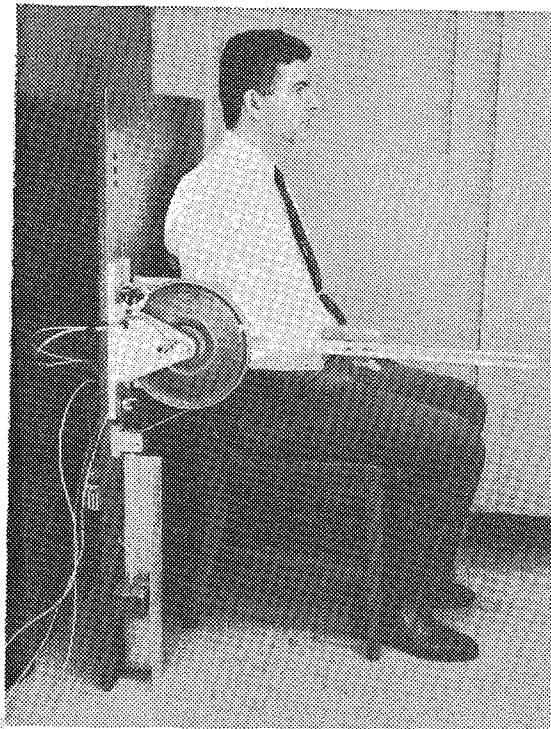
1



2



3



4

Figure 3. Ergographic Equipment. Illustration 1, showing tachometer (A), Potentiometer (B), and load (C). Illustration 2, ergometer and recorder. Illustration 3, pulley assembly positioned for shoulder flexion-extension. Illustration 4, pulley assembly positioned for elbow flexion-extension.

a. Chair

A chair, attached to the backboard, allows the subject to be seated during tests. The primary reason for the chair is to provide a means to establish and maintain the location and orientation of the joint under study. The secondary reason for the chair is to reduce the effects of fatigue in the data taken.

b. Load Subassembly

The load subassembly consists of a beam, a pulley, a weight and supporting shaft and bearings.

- (1) Beam - The beam is a lightweight aluminum member attached to the shaft and used to describe the motion parameters and to transfer the applied load to the subject's hand. Two slotted holes in the beam allow the handle to be used either for shoulder or elbow tests and to adjust to anthropometrics of different subjects.
- (2) Pulley - The pulley converts the linear pull of the applied weights into angular effort or torque on the beam. A 1/8" diameter nylon cord attached to the 4.5 inch radius pulley supports the hanging weights.
- (3) Weights - Lead weights provide the force producing the torque load applied to the subject. Four weights are used to generate torques as follows:

Weight Numbers	Load In Pounds	Resultant Torque In Inch Pounds
1	3	13.5
2	6	27.0
1+2	9	40.5
3	12	54.0
1+3	15	67.5
2+3	18	81.0
4	23.5	106.0

(4) Shaft and Bearings - The shaft and bearings support the pulley and beam, mount the instruments and allow the assembly to be moved in elevation on the backboard in order to make tests on the shoulder and elbow motions. It is to be noted that the backboard can be reversed to allow tests to be made on the left arm as opposed to the right arm arrangement shown in the photographs.

c. Instrumentation

Two detectors are used: the potentiometer for angular excursion and the tachometer for angular velocity. An accelerometer is available, but has not been used, to detect angular accelerations. To date, angular accelerations have been calculated from velocity-time traces.

(1) Potentiometer

A 100,000 ohm potentiometer wired to a one and one-half volt dry cell is used to detect angular displacement. The potentiometer is wired as a voltage divider. The output is wired to the recorder.

(2) Tachometer

A Servo-Tek type SA-740-B-1 D.C. generator with a 20.8 volts/1000 rpm output is used to detect angular velocity. The tachometer is equipped with a $\frac{1}{2}$ " diameter rubber covered wheel in contact with the 10" diameter rim on the pulley to yield a 20:1 angular velocity multiplication over that of the subject. The output is wired to the recorder.

2. Recorder

A two channel model 60-1300 Sanborn Recorder is used to make the position and velocity traces. A time piper records one-second intervals at the edge of the trace. The position trace is generally set at a sensitivity of $1 \text{ mm} = 3^\circ$ while the velocity trace has usually been set at a sensitivity of about $1 \text{ mm} = 3^\circ/\text{second}$.

Myocoder printouts (Figure 4) are correlated with the ergogram (Figure 5). Each Myocoder printout represents the effective energy content during a preset sampling and integration period. The beginning and end of each integration period may be marked on the position trace by a small superimposed pip. In this fashion, the position and velocity of the joint under study can be identified with each Myocoder printout.

Channels				
6	5	4	3	2 1
15	19	14	08	00 04
18	27	10	08	00 08
19	21	11	09	00 08
20	22	08	11	05 08
16	22	00	09	03 08
16	19	09	09	00 05
13	16	09	08	16 08
15	18	13	10	21 08
14	19	02	09	22 05
13	16	09	11	28 05

Channels				
6	5	4	3	2 1
16	20	10	08	07 08
17	23	00	09	00 08
16	20	04	07	04 08
17	21	07	09	08 08
16	22	07	09	01 05
15	19	03	08	01 08
15	17	10	09	11 05
15	16	00	09	19 05
15	15	07	09	22 04
13	19	11	09	23 08

Figure 4. Two Typical Myocoder Tapes showing energy values of each myoelectric signal.

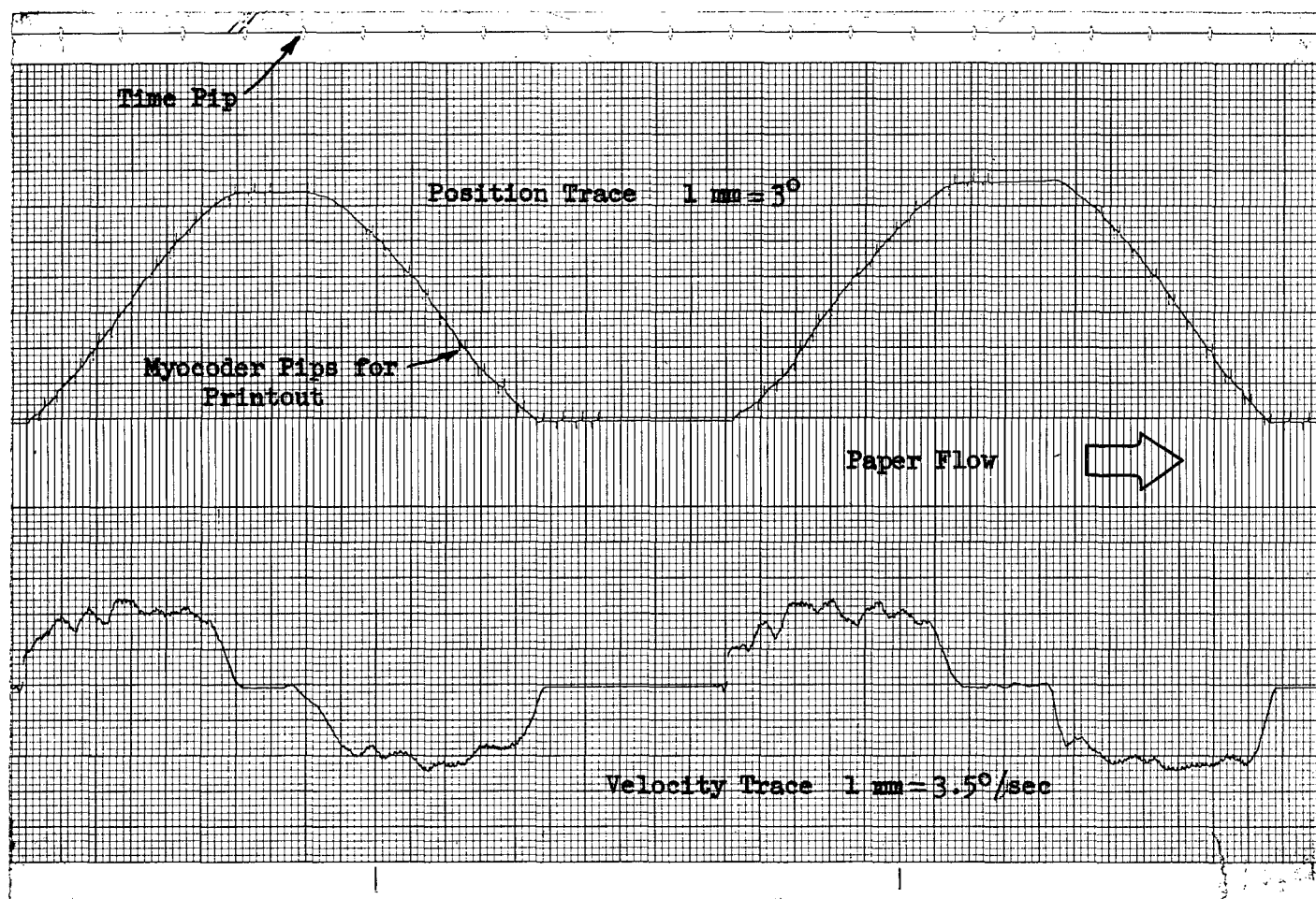


Figure 5. Ergogram for Shoulder Flexion

B. Procedures

1. Objectives

The equipment designed for these studies permits either load or velocity to be used as the dependent variable, while the energy value of the myoelectric signal constitutes the independent variable. Preliminary studies on one subject have been completed which have served to refine data taking techniques and to define issues critical to subsequent parts of this investigation. The following objectives were outlined:

- a. To determine the effect of load on myoelectric signal pattern.
- b. To determine the reproducibility of the myoelectric signal pattern.
- c. To determine the requirements for obtaining an early signal signature indicative of plane of reference and temporal character of the motion being executed.

2. Tests

The subject grasped the ergometer handle with the palm up. He was instructed to raise his arm to shoulder level, and then return to starting position with the arm straight down at the side. When repetitions of arm excursions were made, the subject kept rhythm with the cadence of the Myocoder printer which served as a metronome.

For each repetition six channels of ten time-sequenced samplings of myoelectric data were obtained, thereby providing ten myoelectric values for each repetition. Ergographic data were obtained simultaneously. Electrodes were placed over the anterior, middle, and posterior deltoid, the pectoralis, the supraspinatus, and the biceps brachii (Figure 6). Merthiolate was used

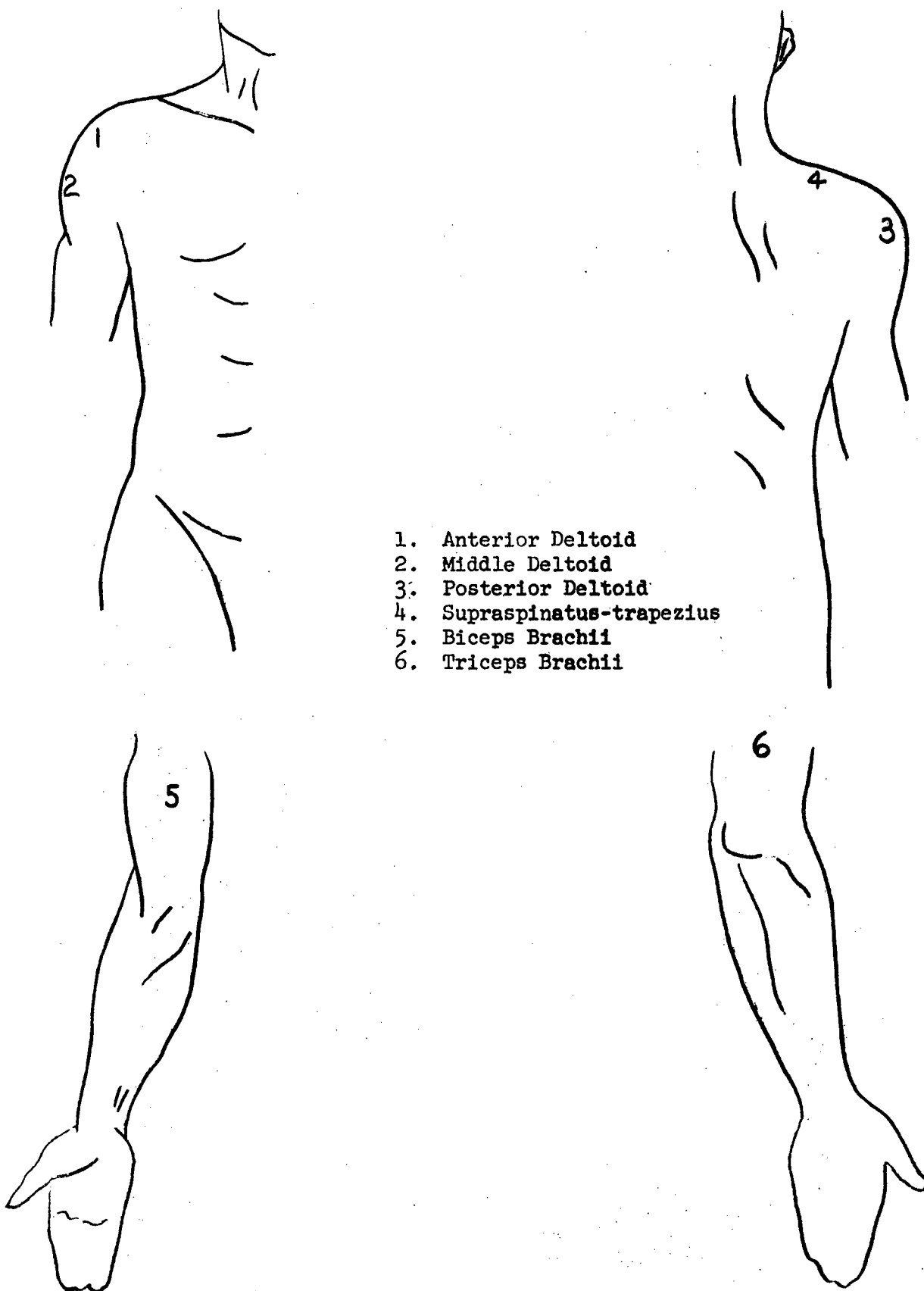


Figure 6. Sites for Electrode Placement

to indicate on the skin, the position of electrode placement.

To satisfy the first objective, loads of 3, 6, 12 and 18 pounds were used. Five repetitions were completed with each load. The order of loadings was determined by using a random table of numbers. All data were replicated three days later to meet the requirements for the second objective. Satisfying the third objective required scrutiny of the data obtained above giving particular attention to the phenomenological character of the data.

3. Data Reduction

Using the total number of repetitions executed with each load, the arithmetic mean was calculated for the corresponding time-referenced myoelectric values (Figure 4). These means were correlated with the torque generated by the contracting muscle, and with the change in position of the extremity. Torques were calculated using an empirical formula (Appendix A) and the position information was read directly from the precalibrated ergograms. The rate of change in position was checked for each repetition to assure that the data were comparable.

IV. RESULTS

A. Load and Myoelectric Pattern

Working against an increased load during shoulder flexion caused an increase in myoelectric values generated by the anterior (Figure 7A) and middle deltoid (Figure 7B). Further, as could be anticipated, the myoelectric values increased as the torque generated by the muscle increased. There was little or no change in energy value of the signals from the posterior deltoid (Figure 7C).

Energy values when lifting the higher loads were not consistently greater throughout the arm excursion, though higher values tended to correspond

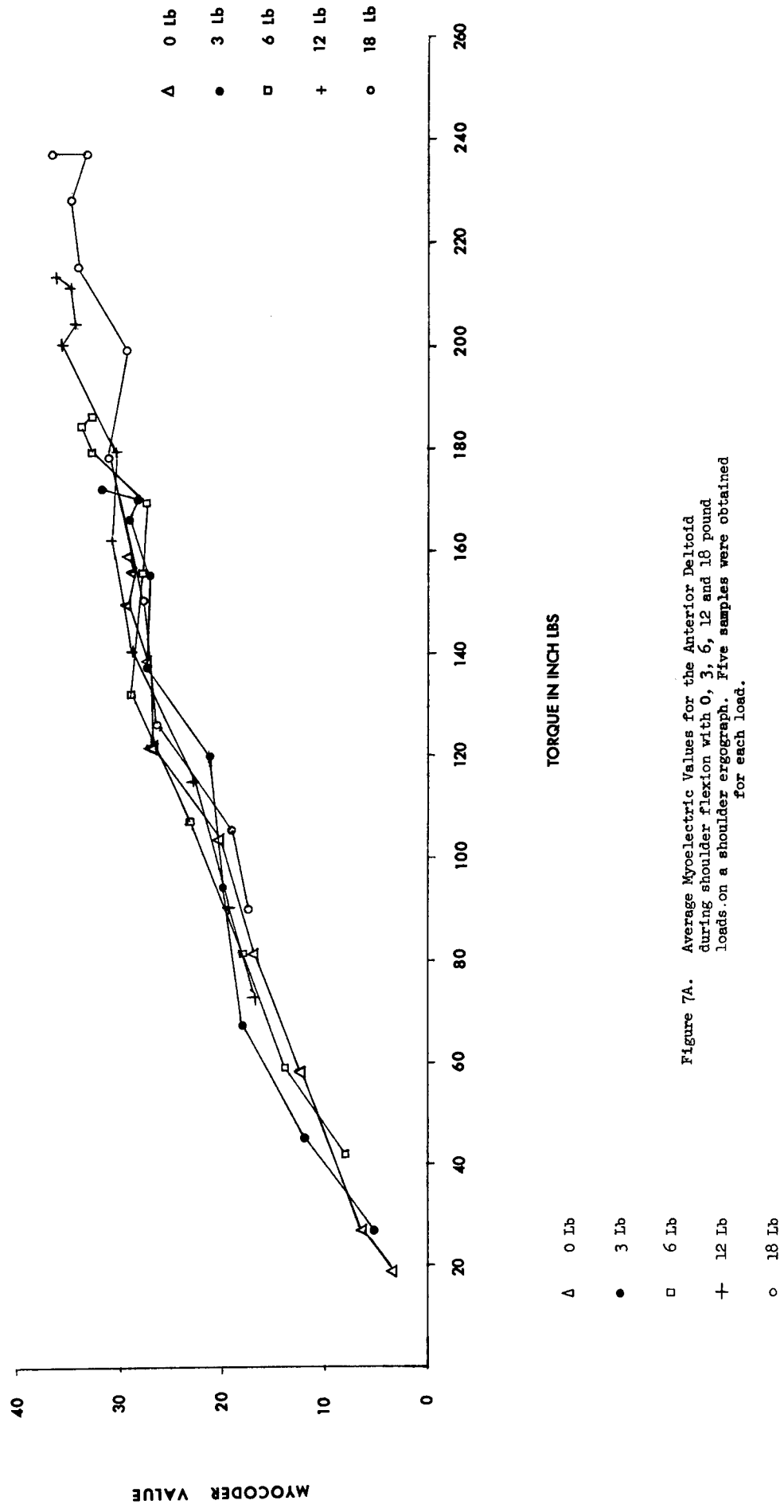


Figure 7A. Average Myoelectric Values for the Anterior Deltoid during shoulder flexion with 0, 3, 6, 12 and 18 pound loads on a shoulder ergograph. Five samples were obtained for each load.

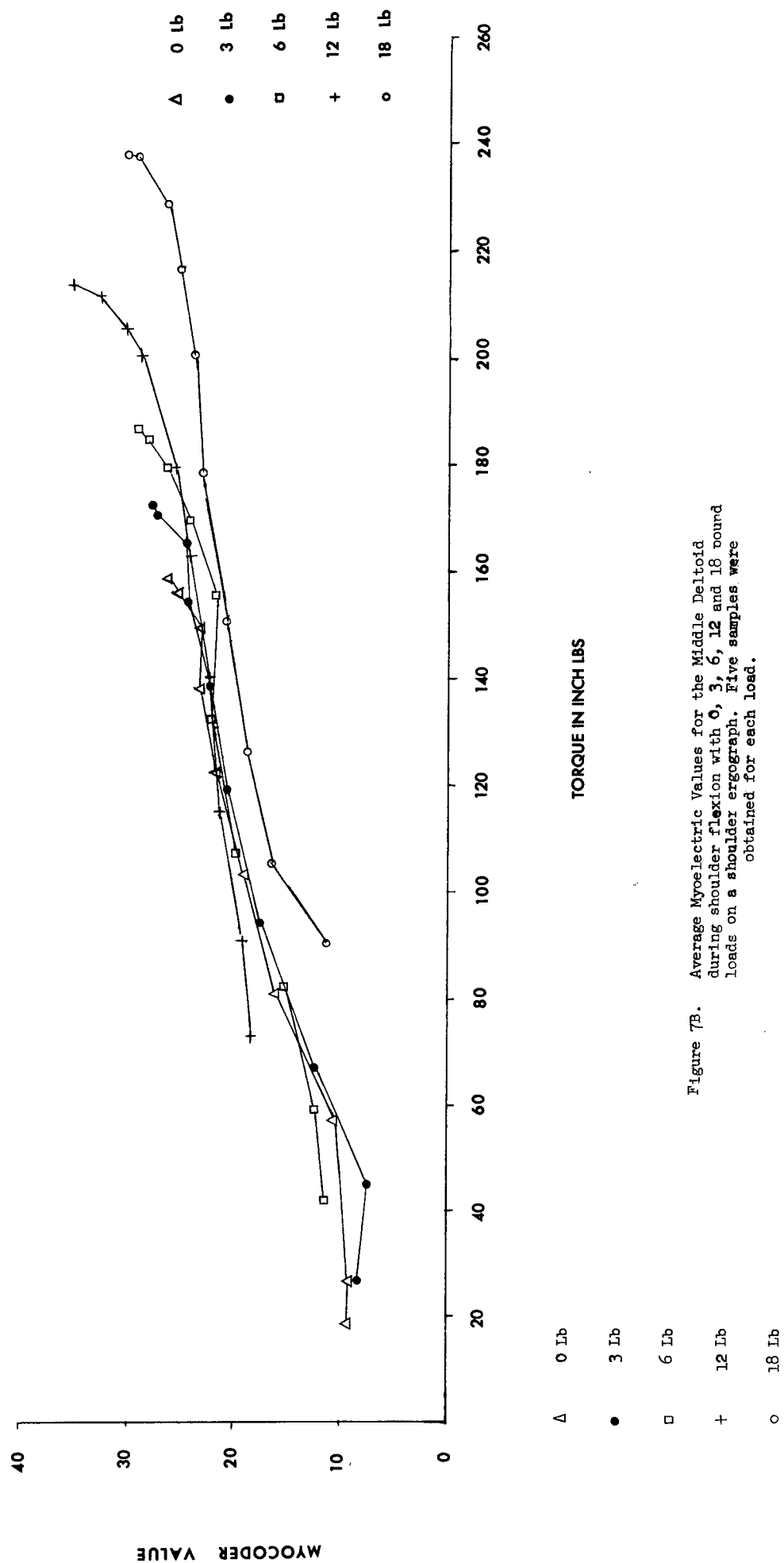


Figure 7B. Average Myoelectric Values for the Middle Deltoid during shoulder flexion with 0, 3, 6, 12 and 18 pound loads on a shoulder ergograph. Five samples were obtained for each load.

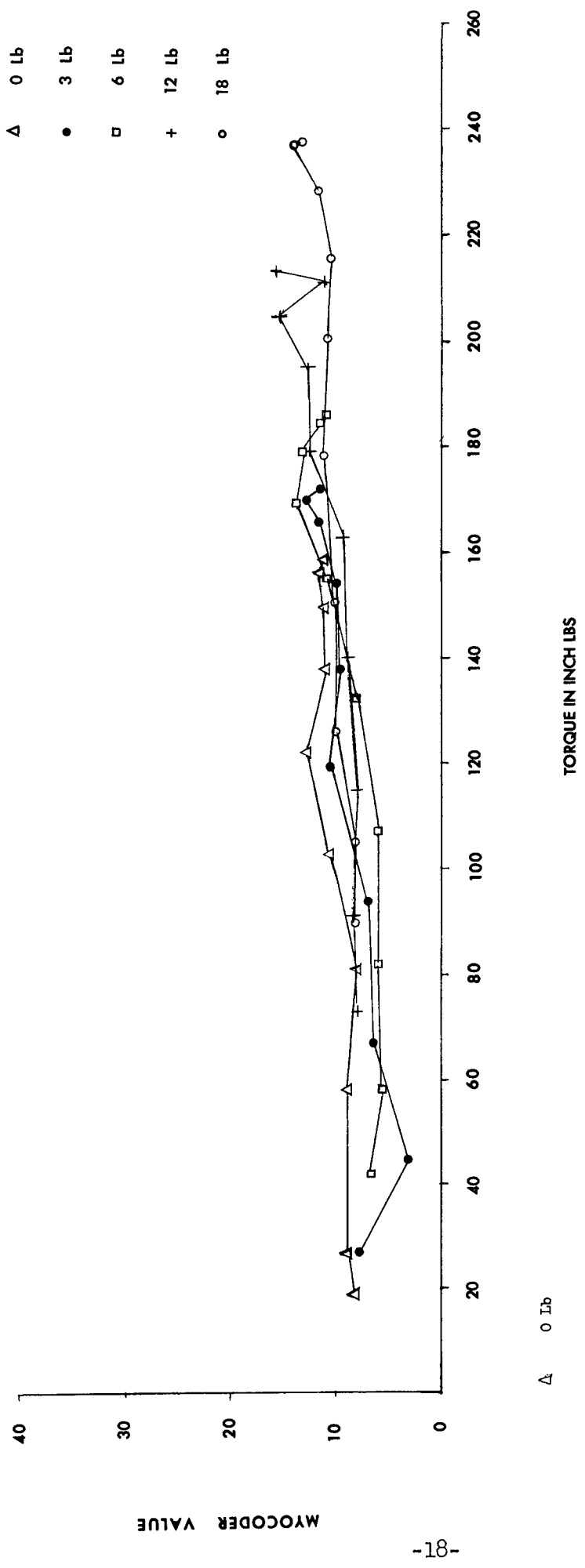


Figure 7C. Average myoelectric values for the Posterior Deltoid during shoulder flexion with 0, 3, 6, 12, and 18 pound loads on a shoulder ergograph. Five samples were obtained for each load.

to the greater loads.

Myoelectric values for the anterior and middle deltoid also increased with displacement, (Figures 8A and B), while little change occurred in the posterior deltoid (Figure 8C).

B. Myoelectric Pattern Reliability

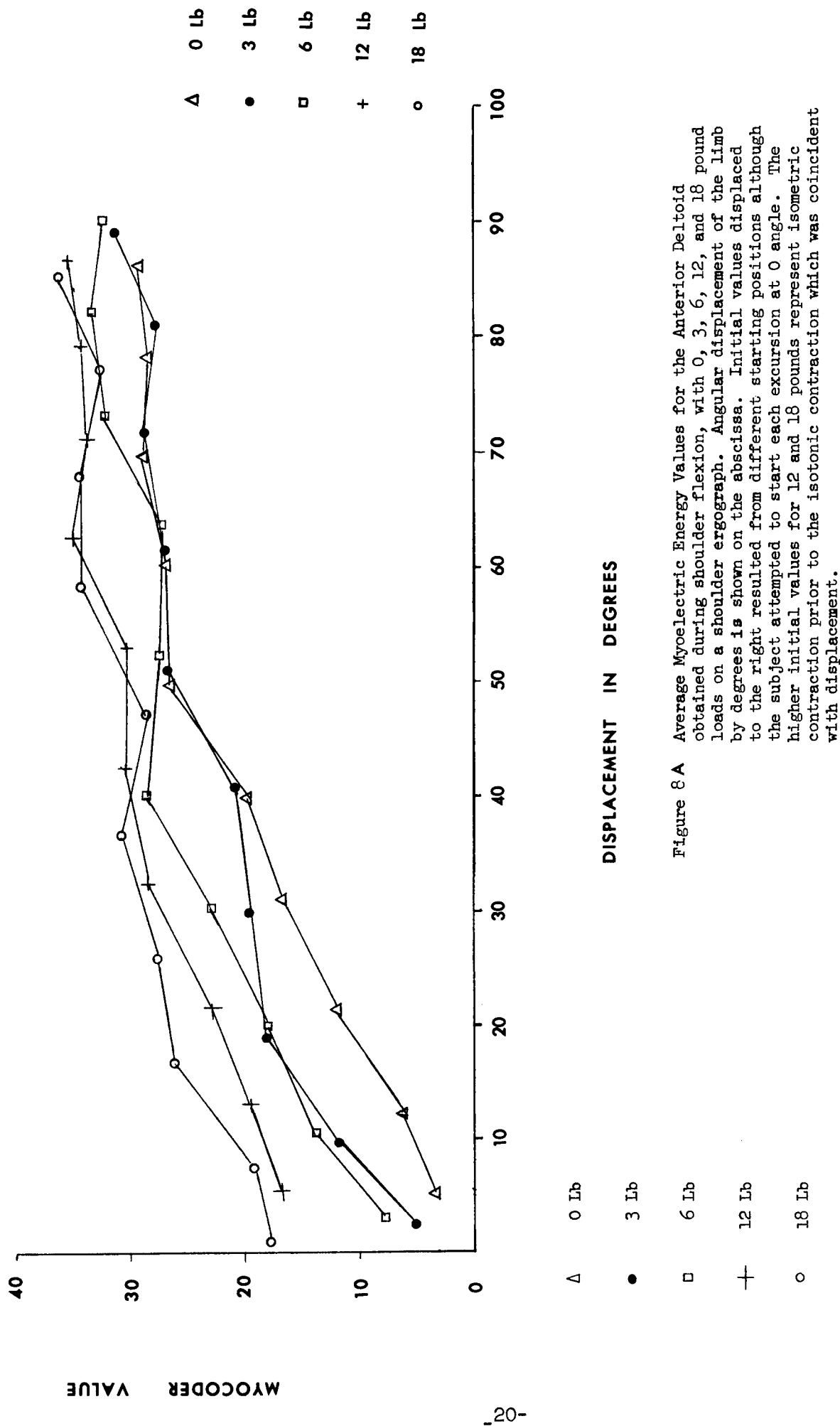
Myoelectric data obtained on a separate test day after removal and replacement of the electrodes are similar in character and energy level as may be seen by comparing Figures 8 and 9. The spread of values for the first test series (Figure 8) was somewhat greater than the second (Figure 9). This finding suggests issues related to muscle training, and motor learning, either or both of which could be contributing factors.

C. Early Signal Signatures

The higher energy values associated with increased loads and occurring prior to displacement (Figures 8 and 9) indicate isometric contractions were required to generate torques equal to the moments imposed by the system before motion could occur. This relationship together with the fact that the values were consistently higher for each increase in load suggests that early signature identification should be sought in the low level isometric signals. Similarly, the low level activity of the posterior muscle fibers during the test motion (Figure 7C) suggests its use as a discriminator.

V. DISCUSSION AND CONCLUSIONS

Obviously the total of human motor performance cannot be electrically programmed and powered. Therefore, a systematic procedure which determines the specific function to be provided is necessary. This procedure should



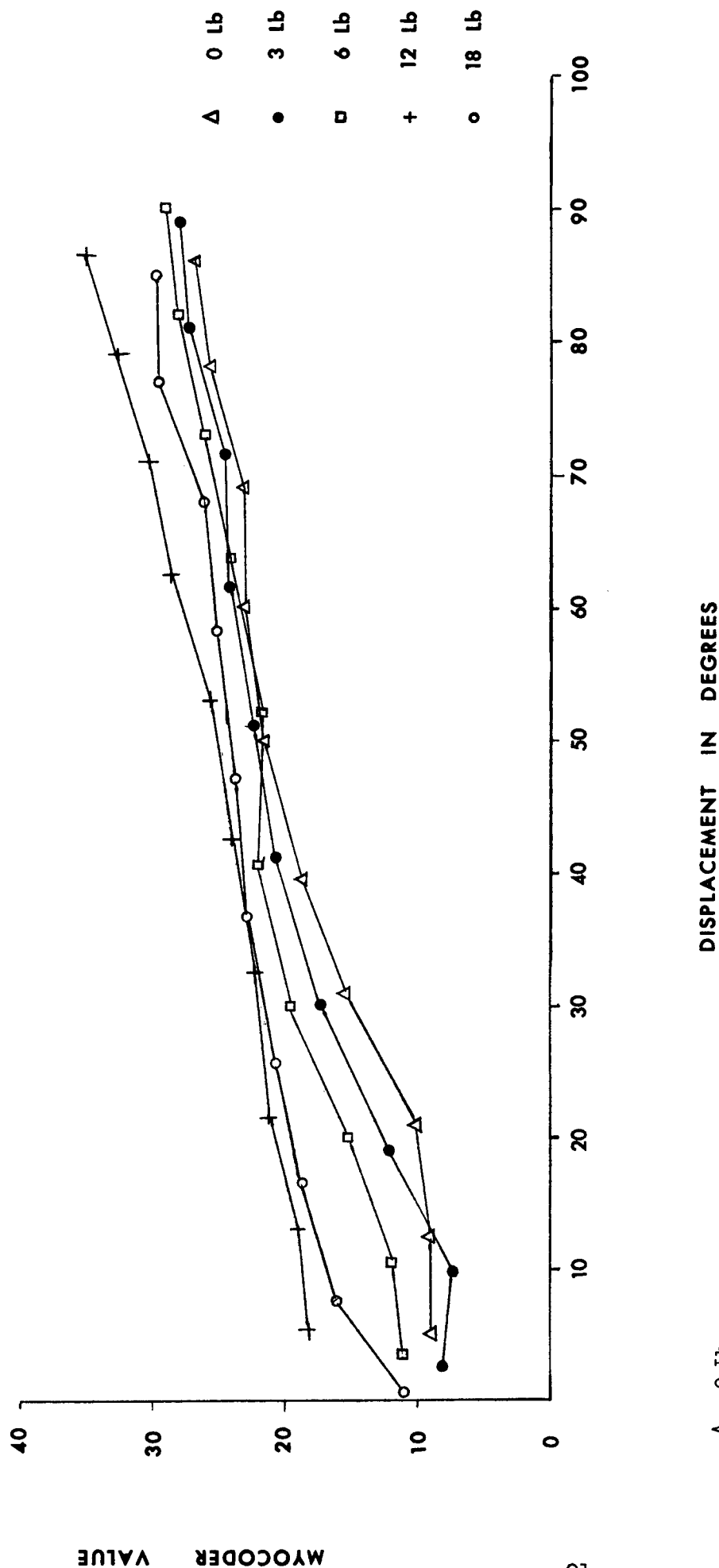


Figure 8B.

Average Myoelectric Energy Values for the Middle Deltoid obtained during shoulder flexion, with 0, 3, 6, 12, and 18 pound loads on a shoulder ergograph. Angular displacement of the limb by degrees is shown on the abscissa. Initial values displaced to the right resulted from different starting positions although the subject attempted to start each excursion at 0 angle. The higher initial values for 12 and 18 pounds represent isometric contraction prior to the isotonic contraction which was coincident with displacement.

Δ 0 Lb
● 3 Lb
□ 6 Lb
+ 12 Lb
○ 18 Lb

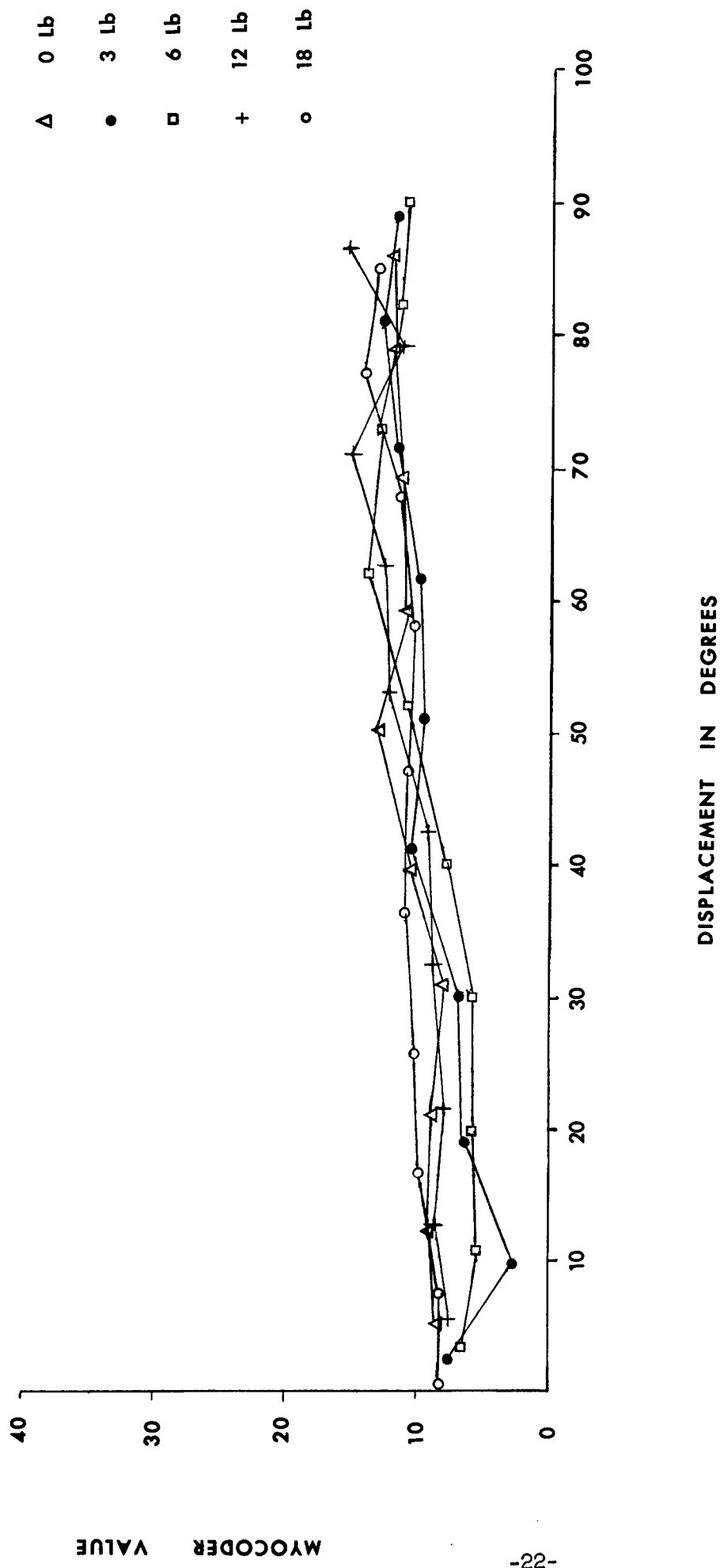


Figure 8C. Average Myoelectric Energy Values for the Posterior Deltoid obtained during shoulder flexion, with 0, 3, 6, 12, and 18 pound loads on a shoulder ergograph. Angular displacement of the limb by degrees is shown on the abscissa.

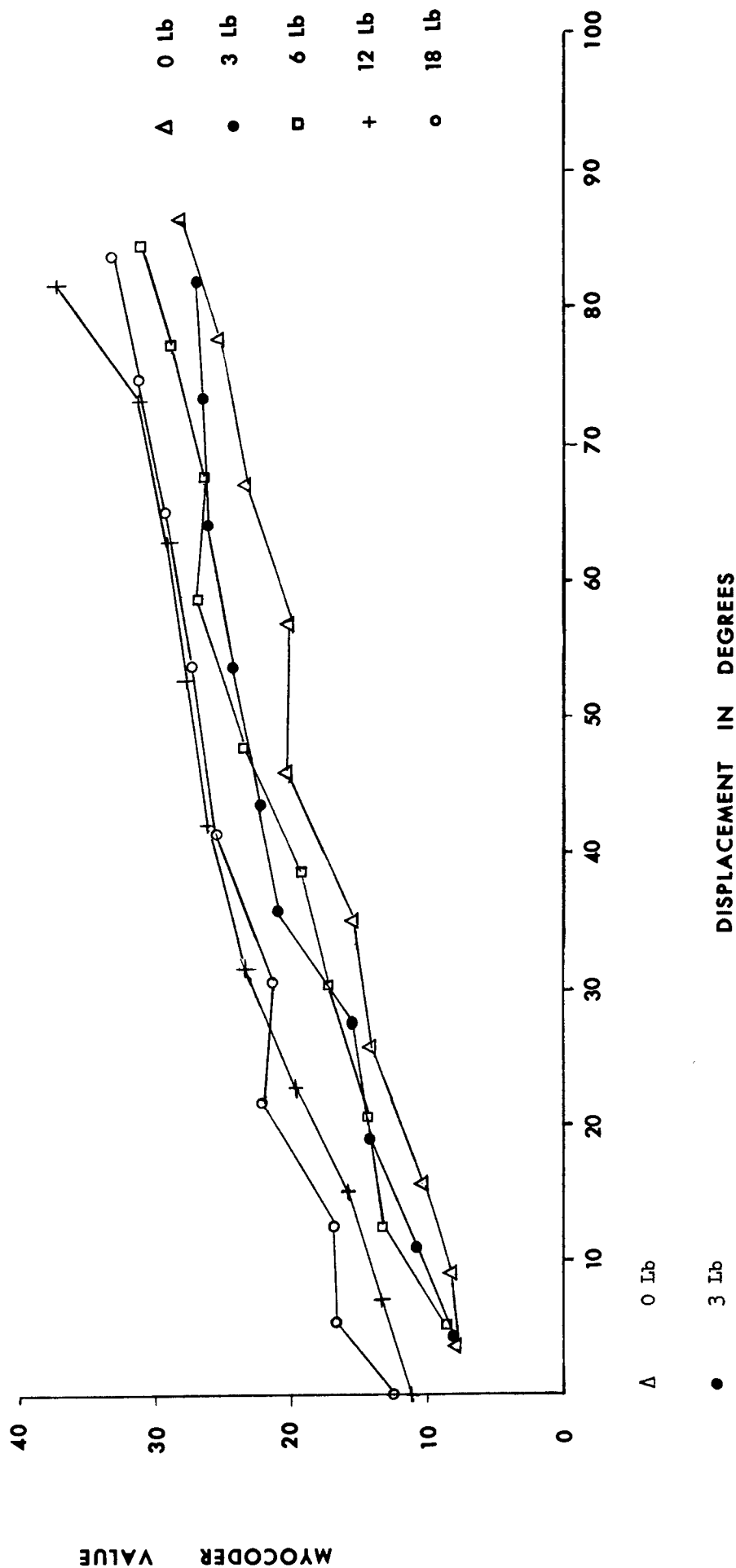


Figure 9. Average Myoelectric Values for the Anterior Deltoid during shoulder flexion with 0, 3, 6, 12, and 18 pound loads. These data were obtained on a separate day, but under the same test-condition as those in Figure 8.

accomplish the following:

1. Delineation of the task to be performed
2. Identification of the control motion
3. Kinematic analysis of muscle action producing the control motion
4. Detailing of required control command motions and muscles to be sampled for computer analysis.

In delineating the task, there must be full awareness and appreciation for the variety of ways by which the performance can be executed and choices should be made accordingly. While the data obtained indicate an increase in energy values with changes in mass, whether or not the spread of values would preclude their recognition as belonging to the same class of activity by the network of the functional device must await further study and analysis. A further problem involves the possibility that, even though proper classification may be made, the scores upon which the network design is based may therefore not provide the discretion required for proportional control.

Identification of the control motion and the kinematic analysis of associated muscle action requires laboratory testing based upon empirical knowledge. Literature study cannot be fully relied upon since dynamic anatomical relationships of a very specific character are involved, particularly as they relate to specific task performance. Therefore, it cannot reasonably be expected that the specific analysis desired will have been made and reported on by another investigator. Such investigations require a muscle group by muscle group analysis always task oriented in order to specify the most desirable muscles to be used as signal sources.

Second and third order problems in addition to that above are raised by consideration for other aspects of physiological variability not yet studied, and the important factor of equipment reliability. The problems of determining force variations consistent with velocity changes, the effects of muscle training, motor learning, and peripheral fatigue on myoelectric pattern must be studied.

The type of electrodes, the materials from which they are made, their adherence to the skin, all are factors relating to the fidelity of signal detection and the elimination of artifacts in data obtained. Similarly, the signal-to-noise ratio in amplification of small voltage potentials is critical to the identification of early signal signature in the command motion as well as maximum balance of the several amplifiers regarding noise levels and calibration.

Within the present contract dates it will be possible to complete only a portion of the problems identified. Therefore, the following have been detailed with consideration for thoroughness and practicability:

1. Completion of studies relating to peripheral fatigue
2. Completion of studies relating to between-subject variability.

This will involve a replication of data reported herein on three to five subjects.

APPENDIX A

EMPIRICAL FORMULA FOR TORQUE

A. General

Torque delivered by shoulder is the summation of moments about shoulder joint.

$$T = M_L + M_A + M_I$$

where $T =$ Torque

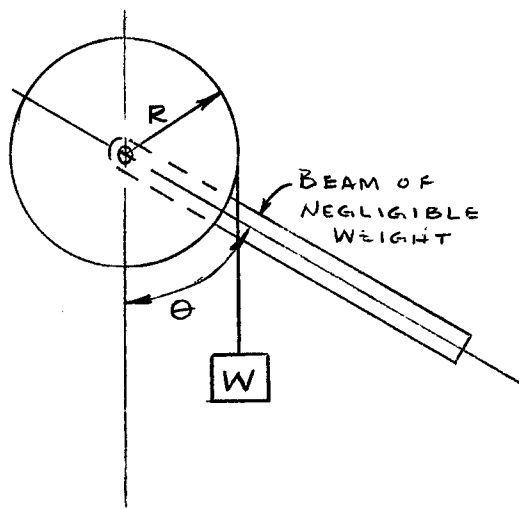
$M_L =$ Moment Due to Load

$M_A =$ Moment Due to Gravity Component on Subject's Arm

$M_I =$ Moment Required to Accelerate Load and Subject's Arm

Moment due to friction may be neglected.

1. Effect of Load



a. Moment due to gravity load

$$M_L = WR$$

b. Moment required to accelerate load

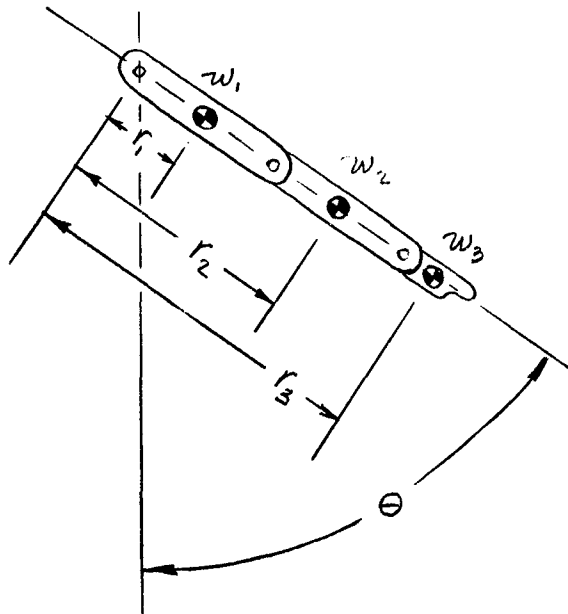
$$M_{IL} = I\alpha = \frac{W}{g} R^2 \alpha$$

where $\alpha =$ Angular Accel in rad/sec^2

$g =$ Gravity constant

Fig. 1

2. Effect of Subject's Arm



a. Gravity moment

$$M_A = (w_1 r_1 + w_2 r_2 + w_3 r_3) \sin \theta$$

b. Moment required to accel.

$$\begin{aligned} M_{IA} &= I \alpha = \left(\sum \frac{w}{g} r^2 \right) \alpha \\ &= \left(\frac{w_1 r_1^2}{g} + \frac{w_2 r_2^2}{g} + \frac{w_3 r_3^2}{g} \right) \alpha \end{aligned}$$

Fig. 2

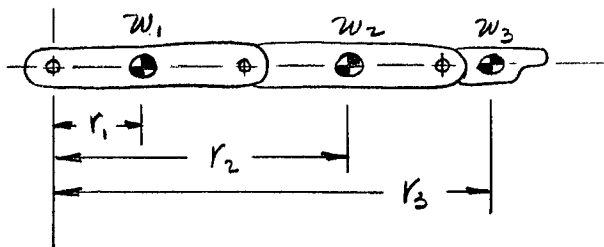
Summation of Moments: -

$$\begin{aligned} T &= M_L + M_A + M_I \\ &= WR + (w_1 r_1 + w_2 r_2 + w_3 r_3) \sin \theta + \\ &\quad + \left[\frac{WR^2}{g} + \left(\frac{w_1 r_1^2}{g} + \frac{w_2 r_2^2}{g} + \frac{w_3 r_3^2}{g} \right) \right] \alpha \end{aligned}$$

B. Specific

In experiments, the applied load w is a measured value. However, the mass and mass distribution in subject's arm is not measured directly.

An initial estimate for order of magnitude was made as follows:



Average Values From Literature

$$w_1 = 9.5 \text{ LB}, r_1 = 7''$$

$$w_2 = 3.6 \text{ LB}, r_2 = 17''$$

$$w_3 = 1.2 \text{ LB}, r_3 = 26''$$

$$\begin{aligned} \therefore M_A &= (w_1 r_1 + w_2 r_2 + w_3 r_3) \sin \theta \\ &= \left[(9.5)(7) + (3.6)(17) + (1.2)(26) \right] \sin \theta \\ &= \underline{150.3 \sin \theta} \text{ for "average" subject} \end{aligned}$$

The subject SM was not average. Hence, preliminary test data gave the following results:

Myocoder Printouts at Different Isometric Loads, Moment in Inch-Lb.

Angle in Degrees	<u>13.5</u>	<u>27</u>	<u>54</u>	<u>81</u>
0	2	4	8	12
30	15	17	20	23
40	18	20	23	27

1. Determine gravity moment of subject SM arm.

At 30°

	<u>13.5</u>	<u>27</u>	<u>54</u>	<u>81</u>
EMG @ 30°	15	17	20	23
EMG @ 0°	<u>-2</u>	<u>-4</u>	<u>-8</u>	<u>-12</u>
	13	13	12	11

$$\text{Arith. Mean} = \frac{13 + 13 + 12 + 11}{4} = 12.1$$

Extrapolating EMG plotted vs displacement an EMG value of 12 @ 0° would correspond to 81 inch pounds torque (intercepted at 0°)

$$\therefore M_A = \frac{81}{\sin 30} = \frac{81}{0.5} = \underline{162} \text{ in. lb}$$

2. Repeat 1 above at 40°

	<u>13.5</u>	<u>27</u>	<u>54</u>	<u>81</u>
40°	18	20	23	27
0°	<u>-2</u>	<u>-4</u>	<u>-8</u>	<u>-12</u>
	16	16	15	15

$$\text{Arith. Mean} = \frac{16 + 16 + 15 + 15}{4} = 15.5$$

Value of 15.5 at 0° corresponds to 105 in. lb

$$\therefore M_A = \frac{105}{\sin 40} = \frac{105}{0.643} = \underline{163} \text{ in. lb}$$

Conclusion:

Gravity moment of subject SM is estimated to be :

$$M_A = 160 \sin \theta$$

This compares favorably with value computed for "average":

$$M = 150 \sin \theta$$

3. Derive working formula for torque required to accelerate subject's arm.

a. For "average"

$$\begin{aligned}
 M_{IA} &= \left(\frac{w_1 r_1^2}{g} + \frac{w_2 r_2^2}{g} + \frac{w_3 r_3^2}{g} \right) \alpha \\
 &= \left[\frac{(9.5)(7)^2}{386} + \frac{(3.6)(17)^2}{386} + \frac{(1.2)(26)^2}{386} \right] \alpha \\
 &= [1.21 + 2.70 + 2.10] \alpha = 6.01 \alpha \\
 M_{IL} &= \left(\frac{WR^2}{g} \right) \alpha = \left[\frac{(18)(4.5)^2}{386} \right] \alpha = 0.95 \alpha \quad (\text{For max. applied load} = 18 \#) \\
 \therefore M_I &= (6.01 + 0.95) \alpha = 6.96 \alpha
 \end{aligned}$$

b. Subject SM was greater than average.

Gravity moment ratio was 160/150.

Conclude $M_I = 7 \alpha$ safe to use.

Empirical Formula for use with subject SM:

From $T = M_L + M_A + M_I$

$$T = 4.5 w + 160 \sin \theta + 7 \alpha$$

where $T =$ Torque, in. lb.

$w =$ Applied load, lbs.

$\theta =$ Angular displacement, degrees

$\alpha =$ Angular accel., Rad/Sec²